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Author:
Aleksander WILUSZ

Supervisor:
Eddie WILSON

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1 Introduction and Motivation

Autonomous cars are currently a topic of a great interest. Around the world the biggest private companies are investing in projects on driver-less technology. There are currently 33 global corporations, including giants like Google, Apple and Tesla, that channel significant resources to autonomous driving (CB Insights 2016). The most innovative countries are allocating large sums of money not only to develop the technology, but also to raise public awareness and introduce necessary legislation (UK Department of Transport 2015*c*);(UK Department of Transport 2015*b*).

***perhaps more here

Although the topic is studied very widely and the amount of literature is enormous this dissertation attempts to identify potential gap in developing a broad understanding of how autonomous vehicles may impact traffic flow.

First part of this chapter introduces the topic of autonomous driving. It discusses current technological development and attempts to identify main challenges in the upcoming decades.

Supported by the literature review, next section states what research gap was identified and why it is worthy to investigate it. Consecutively, a precise statement of research questions is given, followed by a list of aims and objectives of the Dissertation. Another section describes the experiment which was a central part of the project. It also talks about how the original scope of the project evolved from the initial plan to the current state.

Finally, a roadmap of the whole project is given; Starting from the development of software, through the design of the experiment and finishing with the analysis of the results.

1.1 Driverless Cars Revolution

Many expert around the world try to predict how autonomous cars will influence our life in the upcoming decades. Most of them agree that fully automated traffic will become reality around year 2060 or year 2040 in more optimistic predictions (Geiger et al. 2012); (Litman 2014); (Sivak & Schoettle 2015). In the next years we should be observing a gradual change as more and more self-driving cars appear on the roads.

The key factor that influences the steady shift towards fully automated traffic is a broadly understood technological advancement. Although, all the efforts lead towards it, the fully autonomous car has now been yet built anywhere in the world (Litman 2014). This sections talks about the current development of the self-driving technology and about possible scenarios for future development together with challenges that has to be overcame.

Current development of autonomous cars The most recent achievements in the field of autonomous cars are probably best visible through cutting-edge commercial projects such as Google's Self-driving car (Google X 2016), Tesla's Autopilot (Tesla 2016*b*) or Volvo's 'Drive Me' project (Volvo 2015). Google (Alphabet) is probably the most experienced player as it's Self-driving car project started already in the year 2009. However, it is hard to say that it is also the most advanced project as other corporations also reached high levels of the technological advancement and every project focuses on different aspects of autonomous driving (CB Insights 2016).

Google's car is classified at level 3 in automated vehicle classification system proposed by NHTSA (2013) and also at level 3 in a similar classification proposed by SAE (2013). This level of autonomy means that car takes full control over all safety-critical functions but at certain times driver can be asked to retake control (and must do so).

The topic is so interesting that roughly only 60% of companies involved in this business are genuine car-producing companies. Others like Google and Apple mentioned earlier, or a relatively new player Uber saw a new, promising opportunity and decided to expand towards this new emerging market (CB Insights 2016). Figure 1 shows modified Volvo XC90 that was created in collaboration with Uber.

Another company that achieved significant successes is Audi with it's Piloted Driving project. The company managed to develop a racing car capable of beating a professional drivers on a racing track. None the less, Audi is also developing technologies for civil driving (Audi 2013).

While vehicles on 3rd level or autonomy are currently only research projects, there are increasingly more commercially available vehicles that have features characteristic for 2nd level of autonomy. The prime example is Tesla's Autopilot that drives itself on the highway and is able to actively change lanes on a motorway when instructed by the driver (Tesla 2016*c*). Another examples are the latest premium segment cars by BMW and Mercedes that have features such as lane departure warning, adaptive cruise control or traffic jam assistant (BMW 2015); (Mercedes 2015). According to the guidelines by NHTSA car classified on the

Figure 1: Self-driving Volvo XC90 developed in collaboration with Uber. As of August 2016 pilot project is being launch in Pittsburgh, USA (Bloomberg 2016). Photo: Volvo (2015)

2nd level of autonomy must be able to combine at least two of these abilities simultaneously.

Apart from projects run by private companies there are also numerous initiatives supported from public resources. An example of these is the Venturer Project run by a consortium of academic, public and private organizations. The people responsible for this undertaking plan to start tests on regular roads in 2017.

Although, most of these projects bloomed in the last decade, the idea of autonomous or automated vehicles is considerably older. First attempts on automating the driving or part of the driving were made in year 1977 when researchers at Tsukuba Mechanical Engineering Laboratory in Japan built a car that followed white markers and could reach a speed of 20 mph (Forrest & Konca 2007).

Views on the future In the near future we should observe as more and more autonomous vehicles appear on the roads. As mentioned before, the fully autonomous traffic is not predicted to happen before year 2040. Next 30 years should bring significant technological development along with the new legislation and social changes.

It should soon be possible to create a vehicle classified on the 4th or even on the 5th level of autonomy. According to NHTSA (2013) a vehicle featuring 4th level of autonomy should always be able to perform all safety-critical driving operations and driver will not be asked to take over control in any situation. Ford claims to deliver such a vehicle without driver, steering wheel and pedals by the year 2021 (Ford 2016).

It is likely that in the midterm future another idea of connected vehicles may become reality. The idea states that vehicles that are close to each other can communicate and therefore increase safety and add some level of intelligence to their behaviour. Vehicles can also connect to infrastructure and i.e. predict the traffic lights sequence (Narla 2013) ; (Luettel et al. 2012).

Another prediction is that the development of new legislation can be slower than the development of the technology. Although the fully autonomous car may exist, it might be still required to supervise it from the driver's seat.(Luettel et al. 2012). None the less, UK government claims to be aware of necessary changes. The report released by UK Department of Transport titled "The Pathway to Driverless Cars Summary report and action plan" (UK Department of Transport 2015*c*) states that government 'recognises the benefits of autonomous vehicles and is undertaking actions to aid the development of technologies and law that would allow to bring driverless cars on public roads'. Additionally, the UK Department of Transport (2015*b*) states that £19 million is currently being provided to allow testing of automated vehicle technology.

Although majority of the literature focuses on various technical aspects of driverless cars, there are also certain concerns about whether the development is going into the right direction. **?** gives Oxford University's Robotcar as an example and says that the pursuit of full autonomy does not properly recognize the separation between human and machine. The author claims that self-driving vehicles should not be allowed to drive without being deeply connected to the infrastructure, internet and other users.

All in all, in next years we will observe more development in all aspects of autonomous driving. During that time autonomous cars are likely to be still limited to structured, predictable environments. We may encounter some challenges mentioned in this section or find new ones that we were not able to predict (Luettel et al. 2012).

1.2 Implications of Autonomous Cars revolution

Experts around the world argue about the consequences of introducing self-driving cars. The report by UK Department of Transport ”The Pathway to Driverless Cars: Summary report and action plan” summarizes some main benefits of heaving autonomous cars (UK Department of Transport 2015*c*). Most important points include significant reduction of time spent in vehicles and largely improved safety. It is stayed that an average driver could save up to 6 working weeks of driving time in a single year. The claim on potential safety improvements is backed by existing evidence from automated vehicles that are already commercially available and feature level 2 autonomy.

Other important benefits include reduced gas emission and improved congestion. According to UK Department of Transport (2015*c*) vehicles that are connected into one system would be able to drive in the interest of all traffic participants and therefore greatly optimize traffic. Consequently we should observe a reduction in the Total Kilometers Traveled and increased access to vehicles for everyone (UK Department of Transport 2015*c*) ; (MIT Senseable City Lab 2013).

On the other hand, it is argued that autonomous vehicles will not be as robust as expected and traffic parameters will, in fact, worsen(Sivak & Schoettle 2015). Additionally, according to Toyota Scientists (Bloomberg 2013) automated cars may in fact boost fuel use as people will be encouraged to travel farther to work. In the example given in Litman (2014) a family decides to settle further from the city because they can spend time in the car productively rather than controlling the vehicle. In consequence the benefits of faster and more optimized travel will be counteracted by overall increase in road demand. Consecutively the traffic parameters may not improve as expected and the amount of VKT will increase (Litman 2014). This concept is also referred to as Fundamental Law of Traffic Congestion. Any factor aiming at the reduction of traffic can encourage people to travel more. Consequently this will rise overall road demand and the traffic will reach it’s new capacity (Duranton & Turner 2011).

Another possible implication is a change in how the vehicles are used in general. Concepts such as ’sharing economy’ and ’collaborative consumption’ may results in vehicles being offered as a service rather than privately owned. The concept of Vehicles-As-A-Service may also eliminate the taxis in currently known form (Levinson 2015).

1.3 Main challenges to bring Autonomous Cars to the roads

This sub-chapter attempts to identify the main challenges that has to be overcame in the following years. Apart from necessary technological advancement discussed in previous sections it is also important to focus on other factors such as legislation, safety and public acceptance of autonomous cars. Although these issues were identified as major there are also others that were not covered here.

Law regulations on autonomous driving Currently one of the main documents defining the law applicable to autonomous cars is Vienna Convention on Road Traffic. It stays that 'every driver shall at all times be able to control his vehicle'. This means that as long as this document remains in power, fully autonomous driving will not be possible (Economic Commision for Europe 1968). However, the UK government has never signed the Conventions that was accepted by multiple countries around the world including the majority of European countries. Therefore, UK is likely to be in the forefront of the development of autonomous driving as it develops it's own legislation (The Telegraph 2016).

UK government is aiming to achieve a 'light-touch', non-regulatory approach to introducing new legislation. It is recognised that only a certain level of involvement in the development of technology is necessary in order to achieve the fastest progress.

The UK Department of Transport (2015*b*) document covers wide range of legislation issues associated with autonomous driving. The most important matters include possibly to run tests is real traffic, accounting for other road users and responsibility in case of an accident. The latter is a commonly discussed issue as it is nor clear whether the driver, the car manufacturer or someone else should be liable for the actions of autonomous car.

In USA the statement released by U.S. Department of Transportation also recognises the significance of autonomous underlining the priority of ensuring safety of all traffic participants (NHTSA 2013).

Safety Safety is one of the biggest concerns applying to autonomous vehicles. As long as most sources agree that autonomous cars interacting only with each other will create an efficient, accident-free traffic there are multiple questions that has to be answered before that happens. How will the car behave in the situation when it cannot avoid an accident, how will it solve moral dilemmas or who is responsible for accidents are only few of them (Tech Times 2016).

Before the fully autonomous cars appear on the roads there is another safety concern regarding human control. It applies to the cars that are not driving entirely on its own and can ask human driver to take over control in certain siltation. The danger of the handover manoeuvre comes from the fact that once driver gives control over to AI, his or her reaction time drops dramatically (McBride 2016). Recently there was a fatal accident involving Tesla's Autopilot. The exact causes of the accident have not been found yet but one of theories is that the driver was not able to react quickly enough when the car asked him to reclaim control (The Guardian 2016); (Tesla 2016*a*).

Another safety concern applies to emergency situation when the autonomous cars has to suddenly decided between trying to save it's passengers or a pedestrian. This dilemma touches a broad range of philosophical discussion as the answer is naturally not obvious (QZ 2015). The questions whether the cars should kill their own passengers to save a pedestrian is not easy to answer and remains one of complicated moral dilemmas that has to be addressed before selfdriving cars become reality (Bonnefon et al. 2015).

Another possible issue concerns cyber-security. Autonomous vehicles will be connected to the network and it will be possible for unauthorized persons to get into the car's operating system and take control over it's actions (Douma & Palodichuk 2012). Another dangerous situation could a virus spreading through car fleet and causing damage or putting human life in danger. Proper security measures should ensure that such situations will never take place.

Public acceptance of autonomous driving Last discussed challenge concerns public acceptance and awareness. Autonomous car revolution can brings very significant changes to the way we travel. To fully enjoy all benefits public opinion has to under the principles of technology and consciously take part in the upcoming changes. This section analyses results of two surveys asking people from various environments on their opinion on autonomous cars.

First survey was run in year 2014 and included 1500 people from USA, UK and Australia. First findings were that around 60% of people has heard about the autonomous cars and in general have positive opinion on the subject. When asked about possible improvements that self-driving cars will bring most participants indicated fewer accidents, reduced severity of crashes, shorter travel time and better fuel economy. Next, people were asked about their main concerns. The most popular answers were legal liability of drivers, data privacy and interactions with non-self-driving-vehicles (Schoettle & Sivak 2014).

Second survey involved 5000 people from 109 different countries and asked similar range of questions as the one previously discussed. The results indicated that respondents were mostly concerned with software hacking/misuse, legal issues and safety. It was also found that respondents from more developed countries were less comfortable about data transmission (Kyriakidis et al. 2015).

1.4 Interactions between human drivers and autonomous vehicles

This section focuses on on-road interactions between traditional and autonomous vehicles. As it is explained later the matters discussed here lay foundations for the main research questions of this dissertation.

In the next decades driverless cars will be required to successfully cooperate with human drivers. Even when all cars become autonomous, pedestrians, cyclists and other traffic participants must still be able to move around. As discussed in previous section, one of the main public concerns on autonomous vehicles relates to interactions with non-self-driving-vehicles.

Drivewave project conducted by the MIT Senseable City Lab shows how greatly traffic flow can improve when there are no human drivers present. The simulation shows how traffic lights can disappear and vehicles could continuously pass though intersection with minimal alterations to velocity (MIT Senseable City Lab 2013). For the traffic with both types of vehicles implementing such a system might not be possible but Dresner & Stone (2007) suggest a similar reservation system that could manage traffic at intersection consisting both types of vehicles. The idea is that cars approaching the intersection would send information to the intersection manager and receive feedback about action that should be taken.

From the macroscopic point of view it is not clear whether autonomous cars will increase of decrease average number of accidents. According to UK Department of Transport (2015*a*) most accidents are caused by human failure. The main contributory factors are failure to look properly, failure to judge other's person speed or path and driver, carelessness, recklessness or being in a hurry. Driverless cars can potentially be free from these infirmities.

According to UK Department of Transport (2015*c*) the number of collisions should drop but as mentioned before, according to Sivak & Schoettle (2015) the autonomous cars may be less robust than expected and therefore number of accident could rise.

Human driver have certain expectations from other drivers. Things like eye-contact are often important for successful communication. That kind of interaction will be absent in encounters with autonomous vehicles. Moreover, human drivers often posses skills and experience that may not be easy to quantify and program into machine. Therefore driverless cars can, in fact, perform worse in certain situation and as a result during transition period the amount of accident can in fact increase (Sivak & Schoettle 2015).

1.5 Identifying gap in the research

This section describes the primary research question addressed in the dissertation. It explains motivation for the study and how it arose from the gap identified in the current state of knowledge. Furthermore, it lays down all aims and objectives covered within the scope of the project and later supports their relevance with literature discussed in previous sections.

As it was shown, the interest in autonomous vehicles is enormous. Many corporations and governments are channelling very significant amounts of money to various projects associated with autonomous driving. Every involved organization whose aim is to maximise profits is trying to be at the forefront of this upcoming revolution. The amount of research done in various aspect of this new field of science is likewise very large<>.

The majority of attention is given to the development of technology that would allow to construct vehicles with higher level of autonomy. Next wast area of interest focuses on possible implications of the revolution and other things such as legislation, psychological dilemmas and public acceptance that has to go along with the technological development. There is however, little study on how the traffic itself will change during the upcoming years of the transition period. Letting autonomous cars drive among traditional ones will bring far-reaching consequences. The main principles of traffic as we know it will have to be redefined to ensure that we experience all possible benefits of these changes.

On the basis of the gap identified in the research this dissertation attempts to develop a broad understanding of how traditional and autonomous vehicles will interact

with each other and what will be the consequences of these interactions in micro and macro scale.

It is believed that in order to achieve the most benefits from autonomous driving the algorithms governing the self-driving cars have to be optimized for efficient and safe interactions with traditional vehicles. The study focuses on understanding of these interactions.

The primary aim of the research was to predict the impact of autonomous vehicles on the traffic. Results obtained were analysed from the point of view of macroscopic traffic parameters such as average velocity, vehicle density and congestion.

The secondary aim was to inspect particular interactions from the point of view of traffic participants. It was investigated how interactions between two humans compare to interactions between two different types of vehicles.

The main objective of the project was to conduct the experiment that would be a simplified simulation of traffic and would involve human drivers and autonomous cars. The experiment should allow for simultaneous inputs from multiple traffic participants. It would consist of few different scenario that would involve different proportions of human drivers and selfdriving cars.

The secondary objective was to engineer the software that allowed to conduct the experiment. It had to meet all requirement of the experiment and be able to accommodate for altering number of participants. The main part of the software was a network-based, multi player traffic simulation. Each person participating in the experiment controlled one vehicle and made decisions by observing other traffic participants. By looking into how cars interact with each other it should be possible to extract the impact of self-driving vehicles on the traffic.

In order conduct the study a simplified model of autonomous car had to be created. It is important to note that the development of such a model derived from the needs of the primary research and is not a topic of interest itself. Once the right model was established it remained constant through the whole experiment. The algorithm governing the model was derived from well established principles of common car-following models.

Last major objective was to create a realistically behaving model of car dynamics that would respond to participant's commands according to his or her expectations.

1.6 The experiment

The main aim of the project was to look into interactions between autonomous and human-driven vehicles. The main method that was used to achieve this was to create a simulation of traffic with both types of traffic participants. By reviewing the literature it was found that there are numerous car-following models that could be used as a model of human driver. However, no matter how good were these models, they could only work as an approximation of how humans would actually control the cars. It was decided that differences between any of the reviewed car-following algorithms and the unpredictability of real human control are so significant that the study should rely on the experiment involving multiple human participants simultaneously controlling cars in interconnected simulation.

The decision to create such simulation was a key factor that gave shape to the whole project and accounted for the majority of the effort. Out of all work conducted through the project designing and implementing software that would allow to successfully conduct the experiment was the most absorbing and time consuming part.

1.6.1 will be tested, how and why

1.6.2 Initial requirements

1.6.3 Experiment design, real world research

1.6.4 How scope was reduced

The original scope of the project included also in-robotico implementation that would be using remotely controlled ”slot-cars” to simulate traffic. It was believed that physical model would have features that could not be accounted for or predicted in computer simulation. It was estimated for around 50% of implementation effort. However, in the final version of the project the physical model was not implemented. After the project went into development the advantages of creating a physical model appeared less and less attractive. Especially compared to the cost of implementation. Original idea assumed using digital slot-car set with cars and track, as well as computer vision to track vehicles on the track and live video streaming to multiple computers. After more careful consideration the benefits of implementing above described would be very minor or none. In addition to this, implementing the computer simulation consumed more time that estimated.

It has to be admitted that scope was drastically limited in terms of implementation effort. It did not, however, have much impact on the quality of the research and conclusions. One would even venture to say that project should only consist of computer simulation even if more time and resources were allowed for project execution.

1.7 Roadmap

The project consisted of three main parts. First one was software development. This accounted for around 50% of all efforts. The chapter on Research Methodology is mostly dedicated to this. Software section is divided into most significant components that include the design of simulation master, design of client's interface and vehicle's control. The chapter on research methodology also describes how communication between machines was established and the algorithm behind autonomous vehicles. Although these two aspects were integral parts of the software it was decided to write about them separately due to the significance and universality of communication solution and autonomous car algorithm. Most of decisions made throughout the development stage were aimed for successful experiment execution. The design of the experiment is described at the of Research Methodology chapter. The description of how the experiment was eventually conducted is placed at the begging of Finding and results chapter.

The Research Methodology chapter is preceded with in-depth chapter describing literature relevant to the project. The data obtained during the experiment was described in Findings and Results chapter. This chapter also talks about different ways in which data was analysed. The last two closing chapters discuss the results of the experiment, attempt to draw conclusions and generalize findings in wider context.

2 Software engineering

Creating software that allowed to successfully conduct the experiment was the longest and most absorbing part of the project. All decisions starting from the choice of programming environment, through deciding on the structure of the software to ensuring simulation reliability were dictated by the requirements of the experiment. From the point of view of software implementation the experiment required different applications running on multiple machines that would be talking to each other over the network in real-time.

***more planned to be added here...

2.1 Environment choice

Traffic modelling software, (SUMO) SUMO stands for Simulation of Urban MObility. It's an open source framework used for traffic simulation(Krajzewicz et al. 2002). SUMO was first introduced in 2002 and since then it became a popular tool for scientist as well as people involved in practical traffic planning tasks.

SUMO is a purely microscopic simulation which means every traffic participant is modelled separately. The framework is designed to simulate large cities that contain thousands of roads and more than one million of vehicles.

The core of the SUMO package is a logical representation of road layout. Segments of roads separated by junctions are described as nodes and edges. Edges consist of directed lanes. Vehicle's position is described in terms of edge and lane number and distance from origin node. At every step of the simulation interaction between individual simulation entities are computed and all parameters updated. (Krajzewicz et al. 2002)

SUMO is supported by additional pieces of software such as a tool for importing map structure and a plug-in for providing on-line inputs.

The applications of SUMO include designing traffic light sequence, predicting demands on planned roads or creating traffic control systems.

It is a microscopic

It allows to account for multiple factors to create

quick summary of sumo

ROS write about how wors works mostly

Parkin et al. (2016)

else... Choosing the right environment to develop software was a key decision that had crucial impact on all components of the project. After a process of careful consideration it was decided to use MATLAB as a sole development environment for all parts of the project. The initial Project Proposal written by project supervisor, Eddie Wilson suggested using SUMO package as a core of the simulation. It was assumed that a small part of SUMO capabilities would be utilized in combinations with additional software written for the purpose of this project. SUMO features Traffic Control Interface (TraCI) (*link to website*) that gives access to running simulation. The parameters of the simulation like car's location could be potentially retrieved and manipulated in real-time. The additional software would be responsible for network data exchange, visualizing car's surrounding and capturing inputs from experiment participants. Most likely the programming language used for this part would be C++. On the other hand, SUMO was intended for much larger simulations than the one planned. Vast majority of available features would not be used and could rather be a source of potential issues.

A competing idea was to create a tailored application that would be inspired by the structure of SUMO but would be written from scratch. It would be implemented using C++ or MATLAB environment. The main benefit of this approach would be full control of the software behaviour. The main drawback would be rewriting algorithms and structure that already existed inside SUMO. In terms of subjective software preference MATLAB was considered most familiar and least error prone.

Another key question that had large impact on the decision was how to establish reliable communication between machines. It was found that MATLAB supports at least three possible ways of communication that could be used in the project including User Datagram Protocol (UDP), Transmission Control Protocol (TCPIP) and Robot Operating System. This was the main reason why MATLAB was eventually chose for this project. Details of the implementation of network communication are described in the chapter *Communication between machines*.

2.2 Software architecture

***(present tense here..?)

The software in the project consists of three main parts. The most important one is Simulation Server Application. It is responsible for all data processing that is essential for the simulation. The second piece of software is Simulation Client Application. Each participant used an identical copy of Simulation Client Application to receive information about car's surroundings and send acceleration and direction orders to the server. Last part of the software is Communication Agent which was responsible for aggregating information from all clients and sending it to the server. It's existence was dictated by the requirements of network solution described in further chapters. Server, Agent and all Clients' applications were running on separate machines.

Main part of the simulation was main loop that was executing at fixed rate of 16 Hz. All machines used in experiment were synchronized according to Server's clock. The simplified sequence of events across all applications is described in Table 1.

2.3 Simulation Server Application design

Simulation Server Application was at the heart of the simulation. It was responsible for all essential computation, managing communication between other entities and executing code at constant rate. Its design consisted of following classes (appendix: class diagram):

- Simulation - Only one object of this, essential class existed throughout entire simulation. The most important methods were accountable for establishing communication, importing parameters and running main simulation loop.
- Map - Single Map object was created by Simulation. Among other things it contained all information regarding road layout, references to all vehicles, relations between them and future predictions.
- Car - Base class intended to derive other classes from it. It contained features common for both types of vehicles such as velocity and distance calculations and Gipps model.
- Car human driven - Derived from Car class. It contained additional attributes specific to human-driver but only basic methods as most of essential computation was happening within Map class.
- Car autonomous - The Intelligent Driver Model and decision making algorithm were encapsulated within this class. It was receiving limited information about car surrounding from Map object.
- Participant - Additional class crated to separate orders received from participants from car's logic.

The sequence of events in the main loop of the simulation was as shown in Table 2. While Simulation object hold supervision role over whole process, the Map object was responsible

Simulation Server Application	Communication Agent	Client(s) Application
Starting ROS Core and opening UDP ports for Clients and Agent	Connecting to ROS node and opening UDP ports	Connecting to ROS node and opening UDP ports
Setting up simulation parameters	Listening to instructions from Server...	Listening to instructions from Server...
Sending configuration messages to Clients	Listening to instructions from Server...	Receiving configuration messages from Server
Sending start order to Clients and Agents. Starting main loop	Starting main loop	Starting main loop
Main loop		
Sending individual messages to each Client	Sending combined orders from all clients to Server	Sending order to Agent
Receiving combined orders from Agent	Trying to receive from every client one by one	Receiving my location and vehicles' around me
Performing all calculations for clients, map and autonomous cars	Combining orders from all client to one message	Performing calculation and drawing map in viewport
Waiting for next loop iteration	*Waiting for next loop iteration*	*Waiting for next loop iteration*

Table 1: Simplified order of events across all applications. The order of the events in Agent resulted in one frame delay between giving order by Client and receiving it by Server.

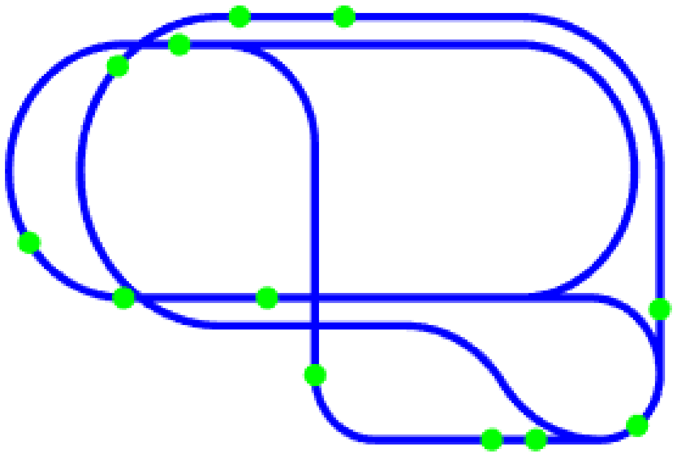


Figure 2: Visualization of current simulation status available via Simulation Server GUI. This example shows third map with 14 autonomous cars.

for the majority of tasks. Once Simulation received information from communication agent and passed it to Map, most commands were called on the basis of Simulation object asking Map object to do certain things and return some values which were then passed to e.g. Autonomous Car. An additional feature of Map class was an ability to create large raster images of whole track. These images were later used by Client Application.

Server Graphical Interface In order to simplify simulation control and supervise simulation status a simple server-side graphical interface was created. It's two main functions were displaying position of each car on the map and setting up each scenario configuration. Figure 2 shows top down view of the whole map available in the GUI. The interface capabilities were allowing to start ROS node, open UDP ports, choose number of cars of each type, choose map, send configuration messages to other parties and start or stop simulation.

Centralized control Running synchronized processes on multiple machines was a significant challenge and a source of potential issues. While the details of network communication are described later, additional, high-level measures were taken to simplify simulation management. The messages send between machines were always in the form of formatted strings. Throughout entire simulation Clients and Agent were always listening to messages

	Class	Event
1	Simulation	Sending each Client its location and orientation together with information about surrounding vehicles.
2	Simulation	Receiving message from Agent containing movement orders from all Clients
3	Simulation	Extracting orders from each individual Client
4	Simulation	Passing updated cars' movement orders to Map object
5	Map	Predicting position of all cars up to 3 seconds ahead based on current velocity and movement order
6	Map	Calculating collisions for current time and predictions made in last step
7	Map	For each autonomous vehicle finding potential collisions with other vehicles
8	Autonomous Car	Making decision on desired acceleration on the basis of information supplied by Map
9	Human Car	Calculating target acceleration on the basis of received acceleration order
10	Car	Calculating traveled distance using 4th order Runge Kutta equations
11	Map	For each vehicle calculating new position and edge on map topological structure
12	Map	For each vehicle calculating new Cartesian coordinates and orientation
13	Map	Preparing individual messages for each Client
14	Map	Drawing all vehicles on the map in Simulation Server GUI
15	Simulation	Saving simulation state at current step.
16	Simulation	Waiting for next loop iteration

Table 2: Order of events in main simulation loop in Simulation Server.

broadcast from Server. This allowed to manage the simulation from Server without any additional configuration on each single computer. There were two basic types of messages: configuration messages starting with letter 'c' and current simulation messages starting with letter 'm'. Configuration messages were usually sent outside of the main loop and contained informations about next simulation session such as map size, map name, initial location of vehicle. These message were also used to start or stop the simulation. To identify the message the first letter was followed by 3-digit code that was understandable for both parties. An example of map size configuration message is shown below.

$$c \quad 108 \quad 0 \quad 360 \quad 0 \quad 260 \tag{1}$$

First number 108 meant that map size is being sent. Rest of the message was then interpreted as x and y dimensions of the current map. Current simulation messages were often more complicated. Below is an example of message send from master to client in running simulation.

$$m \quad 124.56 \quad 189.70 \quad 43.1 \quad 10.8 \quad 1 \quad 2 \quad 141.5 \quad 164.9 \quad 56.2 \quad 135.5 \quad 150.4 \quad 66.8 \tag{2}$$

First 3 numbers meant car's location and orientation. Next two numbers indicated current speed to be displayed on speedometer and binary collision status (Participants were informed when collision occurred). Yet another number indicated how many other cars are in the surrounding. All numbers that followed described these cars' locations and orientations. That data was then used by Client to draw map and all vehicles in the view field. If message was received distorted or incomplete and therefore different from what was expected, it was rejected and values from previous iteration were used.

2.4 Client Application design

Identical copy of Client Application was deployed on each computer used by experiment participants. Main tasks of Client Application included receiving location and orientation, sending acceleration and turn order, displaying part of the map to the participant and harvesting inputs from keyboard. Its design consisted of following classes (appendix: class diagram):

	Class	Event
1	Simulation client	Sending acceleration and turn orders to Agent
2	Simulation client	Receiving locations and orientations from Server
3	Simulation client	Displaying speed and collision status on GUI
4	Map client	Cropping and rotating map image
5	Map client	Displaying cropped map image in viewport
6	Map client	Overlying cars on the map
7	Simulation client	Waiting for next loop iteration

Table 3: Order of events in the main simulation loop in Simulation Client.

- Simulation client - Main class. Responsible for communication with Server and Agent and management of whole simulation from client's side.
- Map client - The most important class. Responsible for such essential tasks as displaying the map and cars in GUI
- Car client - Relatively simple class containing some essential parameters of the car.
- Participant - Identical to the class used by Simulation Server Application. It contained some attributes that should be separated from Car client object.

The sequence of events happening at each loop iteration is shown in Table 3. As it can be seen, it was considerably simpler than Server Application.

Displaying map in view port Displaying car's surrounding was one of the main challenges in the implementation of client's application. As discussed earlier, the experiment design required showing a top-down view of a rectangular area around the car together with car itself and all cars contained in the view port. From the beginning of design process two, radically different approaches to achieve this goal were analysed. First idea was to calculate coordinates of each point required to render scene and display the results using one of MATLAB plot functions. This approach would allow for full scalability and could potentially result in appealing map image without visible pixels. On the other hand the amount of calculations could be much greater as not only cars and road were to be computed but also multiple stationary objects around the road that were suppose to improve the felling of speed (such as trees or houses). The second idea for the representation of view port was to crop and rotate part of the map stored as a large, raster image. The map image was suppose to be 2 to 5 thousand pixels wide and at each loop iteration a part of it would be cropped and rotated according to current car's location and orientation and then showed on client's GUI. Subsequently all vehicles would be plotted over the image. The main advantage of this approach would be a possibility to use complex map image which could be rich in diverse, colourful features. The main drawback would be less attractive, pixelated image as the resolution would be limited. After initial trials with each approach, second one was chosen for implementation. As it quickly turned out, the main challenge was limited computational power of machines used in experiment. One iteration could not last longer than 0.0625 s and preparing map image was only one of the tasks that had to be executed (the frame rate was limited from 20 FPS in later stages of implementation due to Server Application performance reasons). To overcome this problem a custom function to crop and rotate was written. It was used instead of MATLAB methods *imcrop* and *imrotate*. The backbone of this function was written by project supervisor, Eddie Wilson. It was later adapted according to the requirement of the GUI. Once the cropped image was displayed on the GUI, vehicles were plotted over it using MATLAB *patch* function. The overall performance of this solution was sufficient for the needs of the experiment. It allowed to display images 480 pixels wide and tall with plenty of room left for remaining tasks.

2.5 Communication between machines

One of the key factors contributing to the successful conductance of the experiment was reliable communication between machines. Possible network solutions were considered already at the begging of the project and had significant impact on the choice of primary development environment. Although the exchange of data was one of undependable parts of the project, the way in which communication was established was irrelevant from the point of view of the rest of the software. The network solution was only suppose to meet certain requirements derived from the experiment design. After reviewing possible ways of implementation, it was decided to use Robot Operating System which was included in MATLAB's Robotics System Toolbox. Although main intention of ROS was to function as a framework for developing robotics software, it also featured structured communication solution (Quigley et al. 2009). From the point of view of the project, ROS could provide reliable, simple to use way of exchanging data. The initial idea was to create one topic for car's location and orientation and another one for orders from participants (Figure 3). To justify this approach a small game that was exercising almost exactly the same design principle was created. Performance of the game proved to be satisfactory and the project carried on using this solution. However, as the implementation was progressing and tests with multiple clients started, it turned out that subscribing and publishing to the topics takes excessive amount of time and it will be impossible to serve multiple machines and maintain sensible frame rate (which was 20 FPS at that time). In the search for alternative solution other type of ROS communication mechanism was tried which were Services. However, this approach proved to be ineffective too. After further search new idea of using User Datagram Protocol emerged. MATLAB provided simple way to establish communication using UDP which proved to be distinctly faster from original idea. Sending 100 bytes of data as a single string lasted around $0.2\,ms$ while receiving took about $3\,ms$. In the final network solution UDP was used in conjunction with ROS. UDP provided fast way to send and receive data while ROS allowed to: execute code at fixed rate, synchronize multiple machines to Server's clock and manage overruns if code execution took too long. To mitigate the amount of receiving done by the Server, an additional entity called Communication Agent was created. This piece of software running on separate machine was responsible for aggregating inputs from all clients, combining them together into one string and sending to Server. The main reason behind this solution was that receiving one long message took less time than receiving multiple short ones. Figure 4 shows what final communication solution looked like. In tests and during the experiment it proved reliable and easy to use although with some limitations.

The way in which data exchange was implemented was a type of Inter-process communication. According to Rajkumar et al. (1995) this is a considerably challenging task which is often underestimated. Among all objectives that should be met by this kind of software, the most essential ones are probably reliability and scalability. In the case of this implementation it can be said that communication was very reliable however not fully scalable as the frame rate was decreasing if there were more than 7 clients at the same time (Rajkumar et al. 1995).

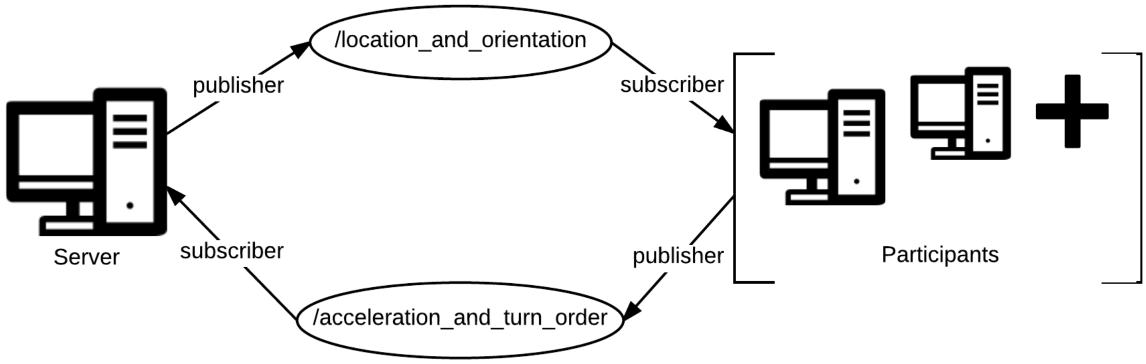


Figure 3: Initial idea for establishing communication using ROS nodes and topics. It was considered to have only one pair of topics for all participants or individual pair for each single participant.

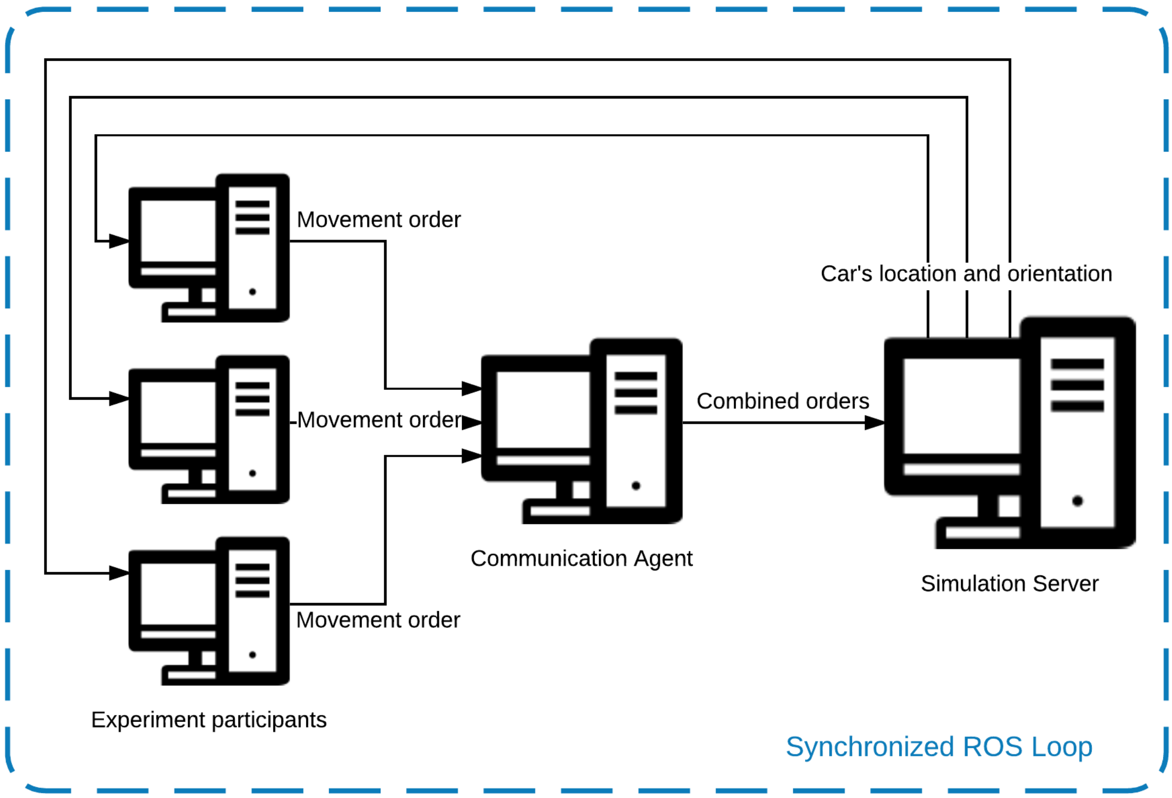


Figure 4: Final communication solution used in the project. A combination of UDP and ROS allowed to have reliable, synchronous exchange of data

3 Experimental design

Experiment design.. The experiment was arguably the most important part of the project. All work done before was aimed at successful conductance of the experiment and all work done after was based on the data collected during the experiment.

style note: *This is all written in conditional because it was a plan and actual implementation is a different story??*

The experiment was planned to involve ten to twenty people. They would be asked to control one of the vehicles in the simulation. Each of them would sit in front of a computer where they could use keyboard and observe the screen. On the screen they would see a top-down view of their own vehicle and it's surrounding. By using the keyboard they would control the acceleration of their vehicle. The instructions given would encourage to explore the map and avoid collisions with other vehicles.

The experiment was planned to consist of three main sessions and one learning session. Each session would feature different scenario which determines road layout, number of human-driven cars and number of autonomous cars. During preliminary session participants would learn how to control the car, how car responds to their commands,how to turn and what the environment looked like. After learning period the first and second phase would commence. Both phases would use identical map but the proportion of traditional cars to autonomous would change. The map shape would be an infinity loop shape where vehicles would have to follow each other and there would be one intersection. It was assumed that such an approach would allow to measure macro parameters of the traffic as both phases would be comparable and the impact of autonomous vehicles could be potentially extracted. The initial choice of measured parameters included average velocity, density, distance covered and other basic statistical parameters such as variance and standard deviation. The scenario in the third phase would use significantly more complex map with 3-way intersections, road exits and road (accesses?). It would feature a similar number of traditional and autonomous cars. The focus of the analysis would be microscopic interaction between cars in various road situations. Number of autonomous vehicles present on the map depended on the number of people turning up for the experiment. Additionally map used for phase one and two could be scaled according to the total number of cars. The instructions given to experiment participants before each phase stated the following:

1. Cover as long distance as possible
2. Avoid collisions with other cars at all cost
3. Use keys described below to control the car
4. When given a choice to turn at the intersection it's your decision which direction you want to go
5. Listen to other instructions

At every step of the simulation all relevant data was recorded for further analysis. In the event of collision the cars would be allowed to pass through each other. None the less, the event was captured and collision alert was displayed for drivers involved in the accident. Collisions were unwanted events that were considered a distortion affecting the results. By allowing the cars to pass, the traffic disturbance was mitigated. Another considered ideas such as teleporting vehicles to another place or manually changing the velocities would probably have greater impact on traffic smoothness. Figure 5 show a screen-shot of Participant's interface.

traffic parameters In order to evaluate traffic performance four key parameters will be measured as suggested in a paper by Beymer and McLauchlan (Beymer et al. 1997).

- Flow - Amount of vehicles in one hour (will be separately evaluated for different parts of the track)
- Velocity - Average velocity of individual car or multiple cars
- Density - Amount of vehicles in for specified distance
- Headway - Spacing between vehicles

Additionally to the parameters above the traffic will be analysed in terms of amount of accidents.

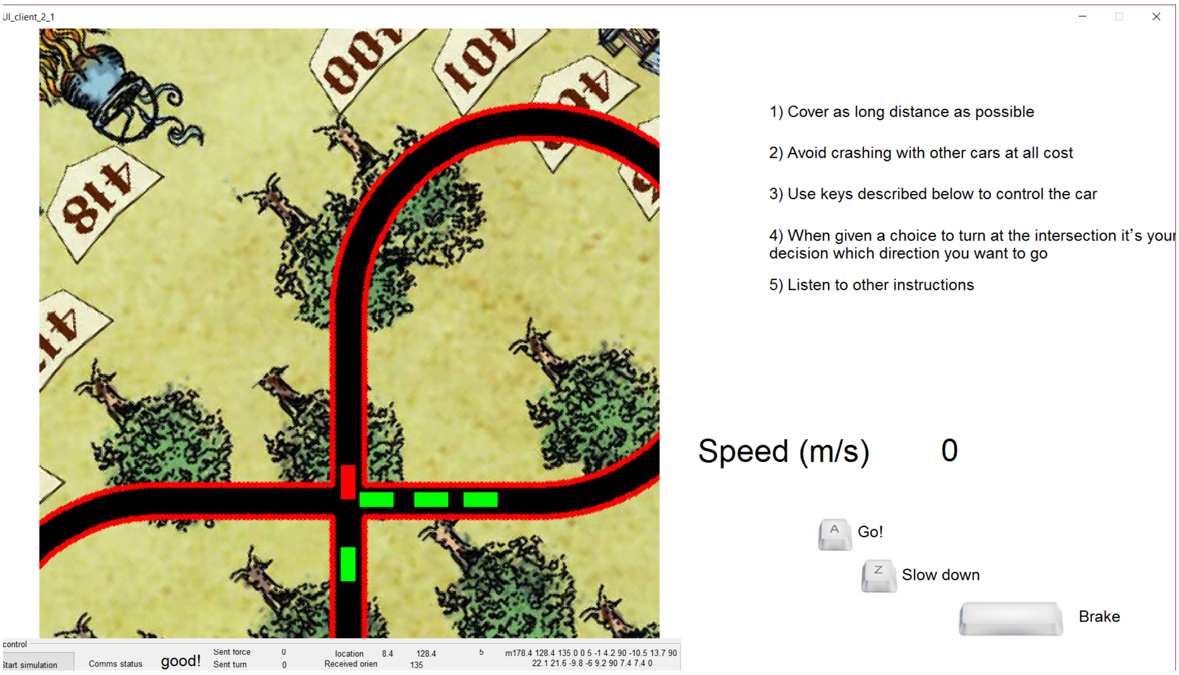


Figure 5: Screenshot of participant's interface. Participant's car is marked in red and all other cars in green. *comment* part of gui is cutted. will fix

3.1 Scenarios

Each scenario specifies configuration of the map, number of human drivers, number of autonomous cars, initial position of each car and length of the simulation. While map configuration had to be prepared before, number of vehicles of each type and time of the simulation could be set at the start of the experiment. This flexibility helped to accommodate for unknown number of people that showed up for the experiment. To ensure reasonable congestion but yet high number of interactions each map was designed for different number of vehicles. A benchmark test with solely autonomous cars and additional empirical tests allowed to establish that every vehicle should correspond to 45 to 80 meters of total track length. In all scenarios participants were not told which car is autonomous and which is controlled by another human. They could, however try to guess the type of the car from how it behaved.

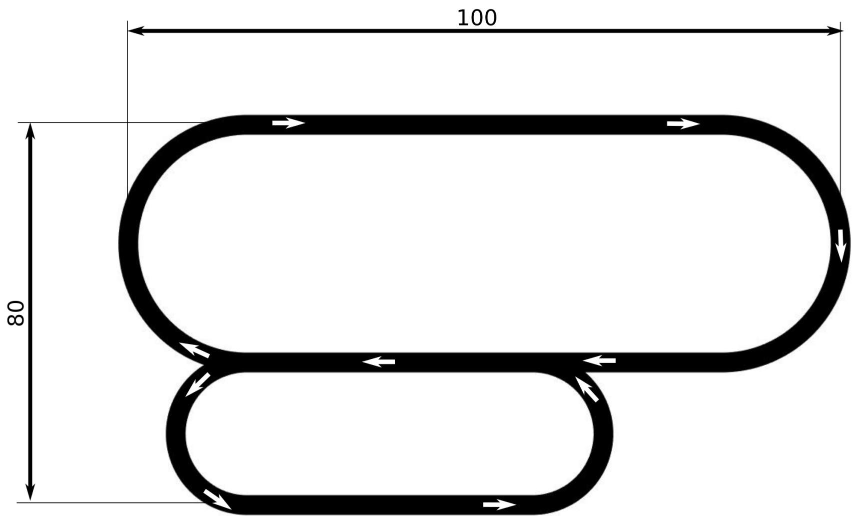


Figure 6: Map used in learning scenario. It featured one road exit and one road split. Dimensions are given in meters.

3.1.1 Learning phase

The learning period involved all participants and one autonomous car. It lasted 2 to 3 minutes and was intended for getting familiar with the simulation. The data from this period was recorded but was not intended for analysis. In that period participants could ask additional questions. The map used in this scenario is presented on Figure 6.

3.1.2 Scenario 1

In the first scenario all participants were involved and there was one autonomous car. The map featured figure of eight shape as showed on Figure 7. The intersection in the middle was uncontrolled as it did not have any priority rule. It was hoped that this way cars would face uncertain situations and interactions will be more vibrant. This scenario was intended to capture interactions in traffic consisting almost entirely of traditional cars. Interactions were either between cars following each other or between cars at the intersection. It was hoped to observe how people are keeping distance to car ahead, how conflicts at intersection are resolved and what are the potential queueing behaviours. Before the simulation started, participants were briefed what is the shape of the map but they were not told how many

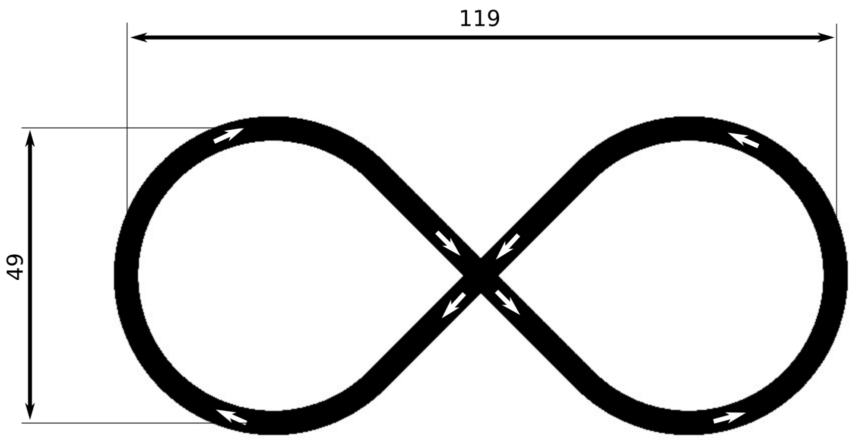


Figure 7: Map used in First and Second scenario. It featured infinity loop shape. There were no road splits and cars had to follow each other. Dimensions are given in meters. Covering the whole map at full speed of $15\,{}^{m}\!/_{s}$ would take 22 seconds. The track was intended for 6 to 10 vehicles.

autonomous cars were in the simulation. This phase was planned to last 4 to 8 minutes depending on the number of participants.

3.1.3 Scenario 2

In scenario 2 around 35% of people taking part in the first scenario was substituted for autonomous cars. This scenario used identical map as scenario 1 (Figure 7) and the total number of cars didn't change. It was hoped that this way the results will be comparable to first scenario. Particular interest was in the interactions at the intersection. The autonomous cars were always letting human-driven cars go first if collision was anticipated. The humans however, didn't know which car is what type and communication happened only via observation of each other's movement. Similarly to previous scenario the planned length would range between 4 and 8 minutes.

3.1.4 Scenario 3

Scenario 3 aimed at microscopic interaction between particular pair of vehicles or groups of vehicles. The map used in this scenario featured multiple types of intersections and was much more complex than previous one as it is shown on figure 8. The amount of human-controlled cars was equal to the number of autonomous cars. The total density of all vehicles was two times lower than in previous scenarios but due of multiple intersections the number of interactions stayed high.

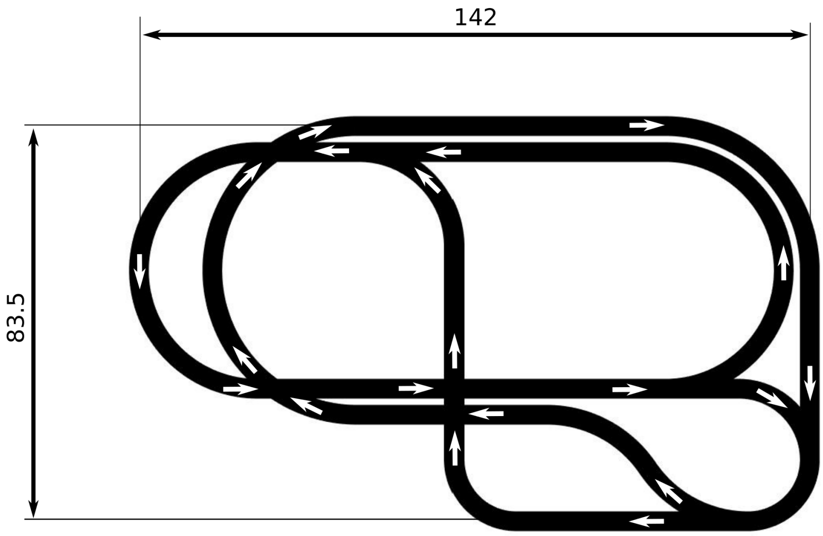


Figure 8: Map used in the third scenario. It featured 2 road splits where drivers could change direction, 2 diagonal intersections,a 3-way intersection and 2 road accesses(?). The total length of all segments was 875 m. Travelling at $15\,{}^{m}\!/\!{}_{s}$ it would take 59 seconds to cover that distance. This was the longest track in the experiment and was designed for 8 to 14 vehicles.

3.2 Client's interface

The main aim of the graphical interface was to mimic what a person driving a car would actually see from the inside of his or her vehicle. Compared to the real world the representation of the environment had to largely simplified. The challenge was to preserve as much of the realism as possible keeping in mind the main principles of the experiment. The cars were represented as coloured rectangles 2 meters wide and 4.5 meters long. Particular participant's vehicle was always position in the middle of the screen while map and other vehicles were moving around it. Roads were 4 meters wide, coloured in black with red boundaries. Each track was overlaid on graphical background with many distinctive features to allow for better sensation of speed (Figure 5). ***(reference to website for photo used in background

Car control using keyboard First things to decide on was how the car was controlled. Fundamentally the car had one degree of freedom as it always went along a predefined path. Only in the event of road split the driver could make discreet choice on which direction to go. The acceleration of the car was controlled by A and Z keys. Pressing A made car accelerate with a value calculated from Gipps' car following model (discussed later). The maximum velocity was capped at $15\ ^{m}/_{s}$. Pressing Z key applied constant deceleration of $-6.5\ ^{m}/_{s^2}$. Additionally drivers could press space bar which functioned as a hand break and applied deceleration of $-10\ ^{m}/_{s^2}$. These number were found empirically so that car responded predictably. Backward movement was disabled for greater simplification. The reason for not using arrow keys was that these keys were used to control car's direction as some intersections featured choice between straight, left and right turn.

Size of view field Another design decision concerned the size of driver's view field. The shape and size of the view field was a square 80 meters by 80 meters where car was positioned 20 meters from the bottom as it is showed on previous Figure 5. It was assumed that for a driver travelling at full speed it should be possible to comfortably slow down to zero when a stationary vehicle suddenly appears in front of it. The amount of time elapsing from first sight of the obstacle to coming to full stop includes reaction time and breaking time. According to (Summala et al. 1998) average reaction time for a vehicle without brake lights is about 2 seconds which corresponds to 30 meters travelled. Breaking at $-6.5\ ^{m}/_{s^2}$ from $15\ ^{m}/_{s}$ takes 2.3 seconds which consequently corresponds to 17.2 meters. Therefore minimal distance that driver should be able to see ahead is 47.2 meters. After initial tests this lower-bound value proved to be too small and after few other trials was extended to 60 meters. Another 20 meters of sight distance was added behind the car.

3.3 Human Car control

The way in which cars were controlled had significant impact on the experiment results. From participant's point of view car's behaviour should be predictable and similar to how real car behaves. The challenge was to achieve this kind of performance using only discreet inputs from keyboard. Graphical interface used by participants allowed to capture multiple keys

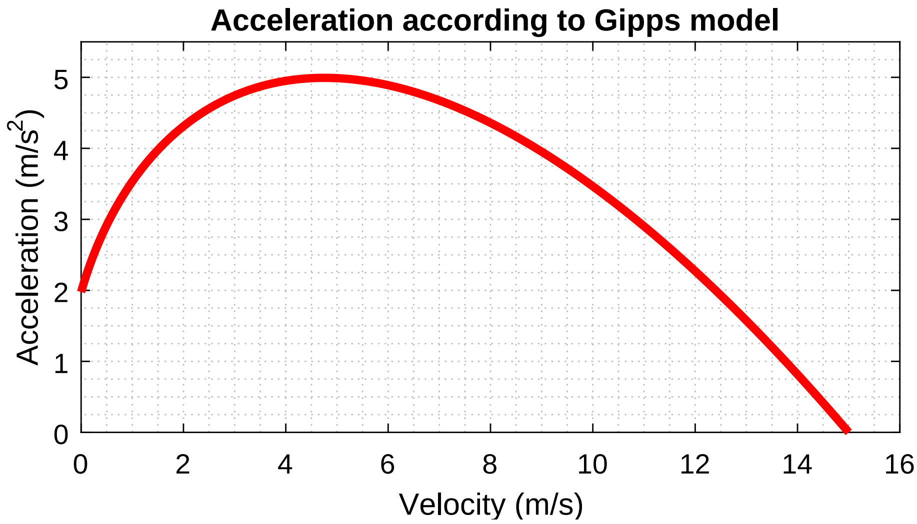


Figure 9: Available acceleration value depending on the current speed.

pressed simultaneously, however resulting acceleration order had to always be one of the following: speed up, slow down, coast or brake. After analysing relevant literature it was decided that car's behaviour should be similar to one of the cars following models (Treiber & Kesting 2013). From The Gipps' Car Following Model given in Spyropoulou (2007) a formula describing acceleration on the basis of current speed was extracted.

$$\dot{v} = 2.5a(1 - \frac{v}{V})\sqrt{0.025 + \frac{v}{V}} \tag{3}$$

In the above equation v is current velocity, $\dot{v}$ is acceleration available at current speed, a is acceleration parameter and V is velocity at which car should not be able to accelerate any more.

Value of a was found empirically to be 5. Figure 9 illustrates how the acceleration value depended on the current velocity. Gipps' model was used only when participant's order was to accelerate (A key). When the order was to slow down (Z key) the applied value of acceleration was $-6.5\,{}^{m}/_{s^2}$. While coasting the acceleration value was 0. To imitate car's dissipating energy coming from aerodynamic drag and rolling resistance the calculated value of velocity was brought down by 0.5% in every loop iteration; This principle applied also to autonomous cars. Last available command influencing car's velocity was braking (SPACE bar) which gave an acceleration of $-10\,{}^{m}/_{s^2}$.

As the experiment was dedicated to city traffic the maximum velocity of traditional vehicle was limited to 15 m/s. Starting from full stop and heaving acceleration button pressed the car would reach that velocity after 11.1 seconds.

3.4 Modelling car dynamics

3.4.1 Car following models

basically literature overview...

3.4.2 Autonomous Car model

Creating an adequate self-driving model was one of the key tasks that had very significant impact on the experiment. The requirements of the experiment stated that autonomous cars should be able to travel among traditional vehicles, avoid collisions and follow default route. In order to ensure validity of the results the model should aim to preserve the most essential features of real autonomous vehicles. The challenge was to identify these features and implement them to the possible extent.

Intelligent Driver Model From the point of view of other traffic participants it would be expected that autonomous car's behaviour was familiar and predictable to some extent (Sivak & Schoettle 2015). In order to ensure such performance in this simulation, the model governing the autonomous car was based on Intelligent Driver Model which is one of the most popular car-following models often utilized in traffic simulations (Treiber & Kesting 2013). The model is described with following formulas:

$$\dot{v} = a\left[1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*\left(v, \Delta v\right)}{s}\right)^2\right] \tag{4}$$

$$s^*\left(v, \Delta v\right) = s_0 + max\left(0, vT + \frac{v\Delta v}{2\sqrt{ab}}\right) \tag{5}$$

Where a is maximum acceleration, v is current velocity, v_0 is desired velocity if there are no cars ahead, δ is acceleration exponent (the grater the value, the later the reduction of acceleration when approaching the desired velocity), s is current distance to the car ahead and s^* is desired distance. In the second formula s_0 is minimum gap, T is minimum time gap and b is comfortable deceleration. The values of these parameters were taken from Sivak

Parameter	Value
Desired velocity v	$10\ {}^{m}\!/_{s}$
Time gap T	$0.8\ s$
Minimum gap s_0	$7\ m$
Acceleration exponent δ	4
Acceleration a	$5\ {}^{m}\!/_{s^2}$
Comfortable deceleration b	$7\ {}^{m}\!/_{s^2}$

Table 4: My caption

& Schoettle (2015) as typical values for city traffic and altered according to the specificity of this simulation (Table 4).

Accounting for traffic coming from different directions For the purpose of the simulation IDM had to be expanded beyond simple car following. Just as a real autonomous car would do, the model used here observes other traffic participants. For every car in the radius of 60 meters it detects it's current velocity and estimates position from now to 3 seconds ahead. If collision is anticipated, certain parameters of IDM are overwritten. A simplified algorithm governing this behaviour is shown on Figure 10. It allowed for smooth, predictable behaviour in almost all situations.

3.4.3 Comparison with human driver

Figure 11 compares behaviours of autonomous and traditional car. It can be seen that although profiles have fairly similar shape, there are some significant differences. And so, while traditional car's max speed is higher, its acceleration is slower compared self-driving one. Additionally, braking profile of autonomous car is smoother than human-driven one.

FIX THIS GRAPH:

3.5 Experiment execution

The experiment took place on the 24th of August 2016. 12 people people turned up for the it. The group was divided into 2 smaller groups of 6 people each. Once first group completed all tasks, another one was asked to begin. The reasons to split people into two groups were of

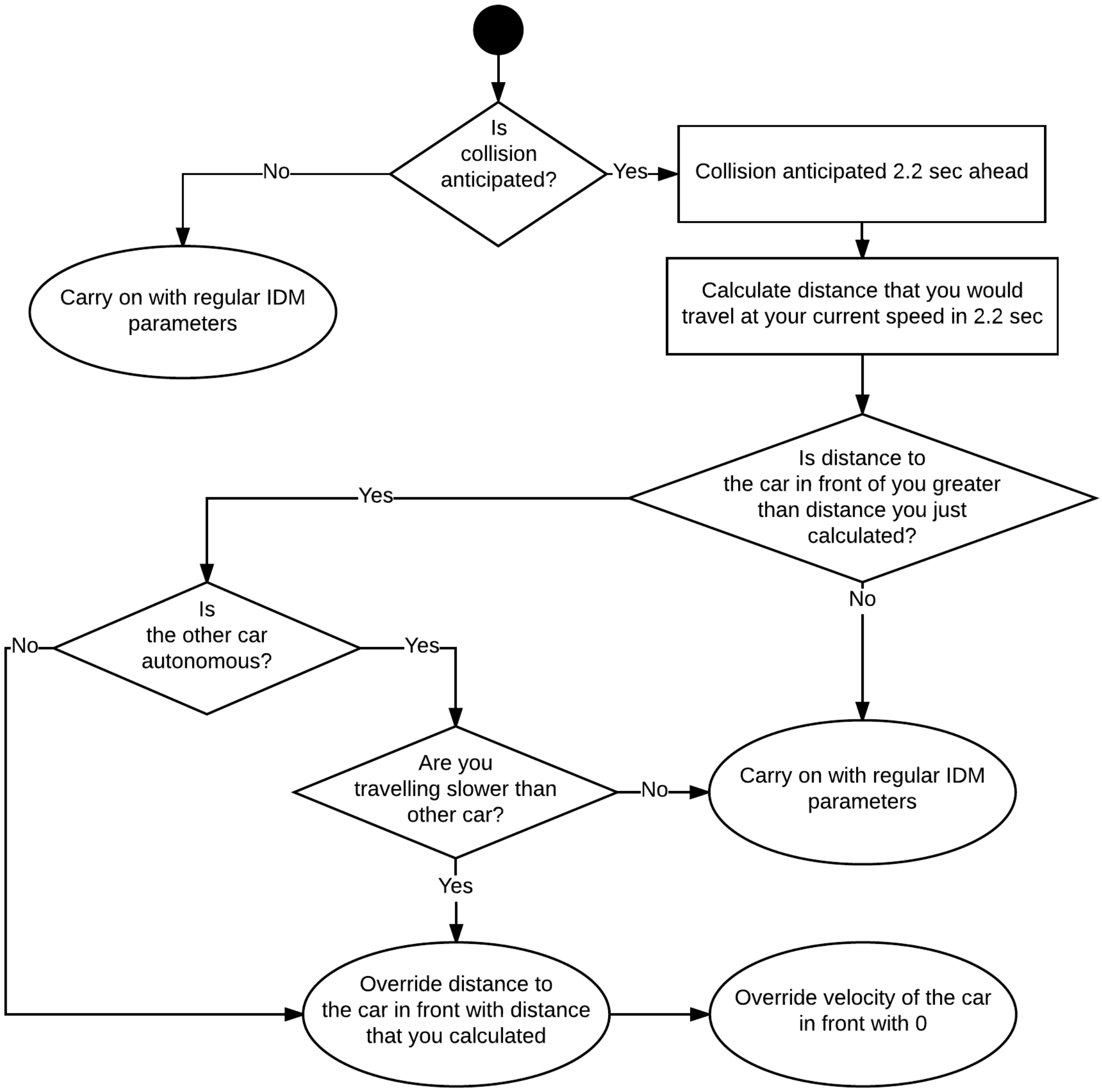


Figure 10: Algorithm governing the behaviour of autonomous car. It was executed for each car at every time step of the simulation. It allowed for very smooth interactions if another autonomous car was encountered and very cautious ones with human drivers.

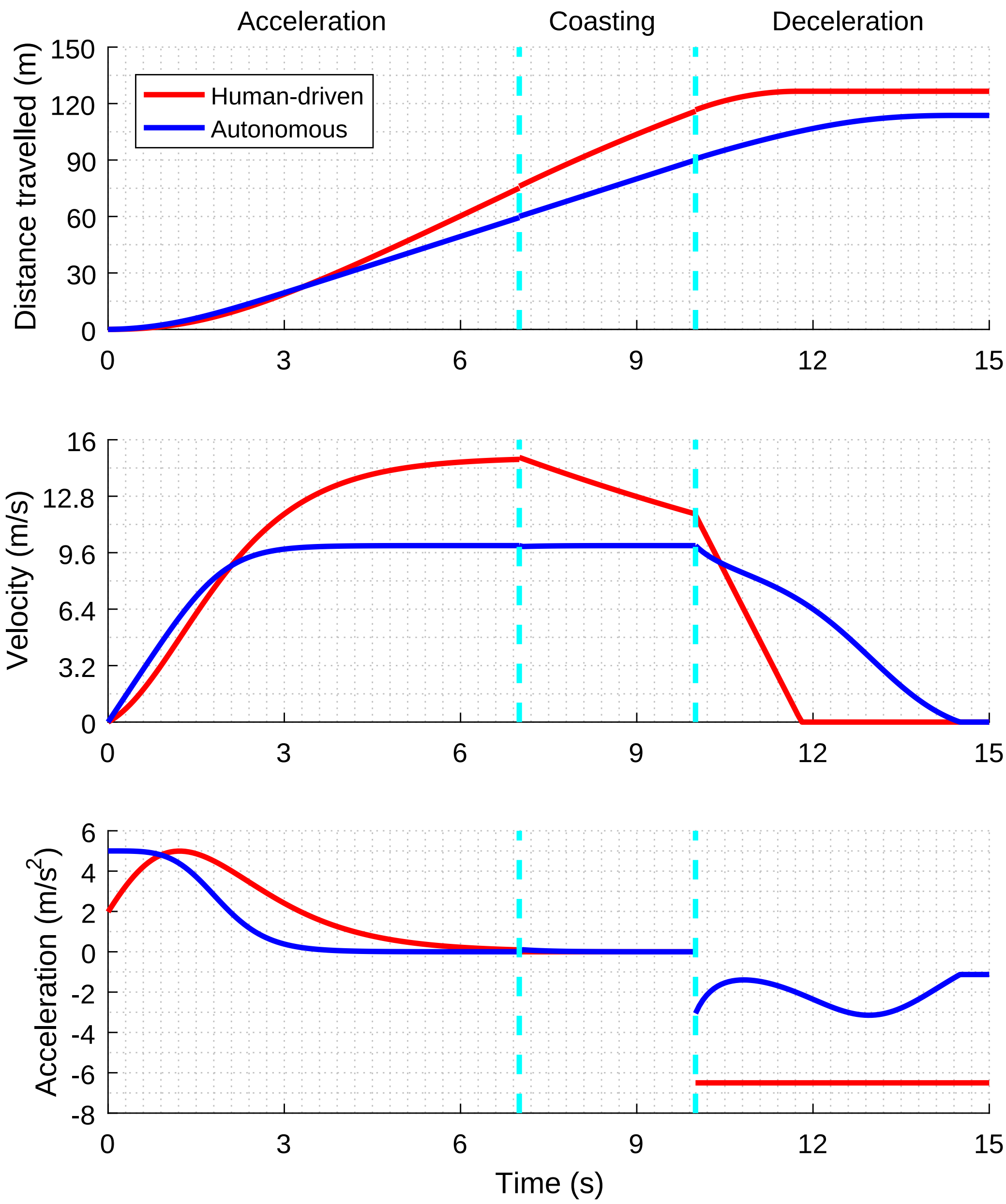


Figure 11: Behaviour comparison of Autonomous and Human-Driven cars in terms of distance travelled, velocity and acceleration. First section on the left corresponds to both types of vehicles accelerating from zero velocity. Middle section shows coasting when Participant's acceleration is 0 and autonomous car maintains maximum velocity. Section on the right shows Participant slowing down at $-6.5\,{}^{m}/_{s^2}$ and Autonomous Car detecting stationary object 30 meters ahead.

technical and research nature. A technical problem arose shortly before the experiment was due to to start. It turned out that from participant point of view the simulation gets considerably laggy if there are more that 7 people playing at the same time. The original frame rate was dropping to few frames-per-second which was unacceptable as it would greatly distort the simulation and whole experiment. From the point of view of experiment methodology heaving two groups conducting identical tasks had beneficial impact on the conclusions that could be drawn from the experiment. It is a common practice to run experiment more than once to detect potential anomalies and have more generalized data(***here use Design and Analysis of Experiments," Handbook of Statistics book).

Experiment was advertised as "Autonomous Cars Simulation". Invitations were sent privately to particular persons. The only information revealed to potential participants stated that experiment will consist of a couple of sessions and they will be asked to drive a car in computer simulation. Participants were promised £10 reward in form of Amazon.com® voucher and catering available before and after the experiment.

Each of the participants was asked to sit in front of one of selected computers. In front of them there were 3 documents: Consent Form, Participation Information Sheet and Questionnaire. (link to appendixes) ***some more content here ...?

3.5.1 Questionnaire

Each of the participants was asked to complete short questionnaire. (link to appendixes). The purpose of the questionnaire was to collect data that later could be used in association with experiment results to create a driving profile for particular person. The exact way in which this data will be used in analysis was not established before the experiment. None the less, it was attempted to ask about things that could be associated with performance of each person.

The survey consisted of 12 questions which can be divided into 4 sections. There were 2 questions asking about gender and age. Next it was asked whether a person played any racing computer games and is familiar with controlling the car with arrow keys. The third section was conditional to the possession of driving licence. If the answer was affirmative, further questions asked about past accidents, subjective evaluation of person's driving style and irritating behaviours they encounter of the roads. Last question asked about opinion on how the traffic will change when autonomous cars are introduced.

3.5.2 Minutes

The experiment started by reading the Participation Information Sheet to all participants. First paragraph stated rights of experiment participants and how the collected data will be used. Second one explained the task in short and concise way. The exact instructions that were given stated as follows:

”*If you decide to take part in the study, you will be asked to drive a car in on-line traffic simulation. You will be using computer keyboard to control your car. Your main objectives is to cover as long distance as possible and avoid crashing into other cars. There will be 3 phases. Each will last 8 minutes, feature different map and different amount of autonomous vehicles. First phase will be preceded with 3-minute- long learning period when you will be able to learn how to play the game. All additional instructions will be given to you before each phase in form of power point slides. Before starting the simulation you are asked to complete a short survey to describe your driver profile.*”

Rest of the document considered health warnings such as epilepsy and past accidents. Next, participants were asked to complete the Questionnaire described above and sign the Consent form. Once that was done they were told once again what is their task, how to control the vehicles and what the next phase will look like. Eventually the main part of the experiment commenced. It consisted of consecutive phases as described it table 5.

The lengths of each phase were considerably shorter than planned. The initial schedule, however, did not account for heaving two streams of people. After the main part of the experiment finished, participants were debriefed and invited for catering. Entire experiment lasted around 1.5 hours and in total 31 minutes of simulation data were harvested.

4 Experiment results

The analysis of the data could be divided into two parts. First one is dedicated to finding patterns, observing dependencies and evaluating particular group and participants. Second one proposes a range of hypotheses which were consequently tested with proposed methods against the data collected. The discussion of the results was placed in next chapter.

Phase	Scenario	Human-driven vehicles	Autonomous vehicles	Lenght
Group 1				
Learning	Learning	6	1	1:45 min
1	Scenario 1	6	1	3:22 min
2	Scenario 2	4	3	4:12 min
3	Scenario 3	4	4	4:09 min
Group 2				
Learning	Learning	6	1	4:33 min
1	Scenario 1	6	1	4:07 min
2	Scenario 2	4	3	5:03 min
3	Scenario 3	4	4	4:51 min
4 (additional)	Scenario 3	6	4	2:24 min

Table 5: My caption

Data collected during the experiment was considerably rich in features and lots of regularities could be potentially found. On average participants changed acceleration/deceleration commands 73 times per minute. Figure 12 shows a snapshot from simulation playback.

Initial choice of parameters measured across data set was different from what different from what was calculated in the process of data analysis.

4.1 Observations

***some introduction to chapter here

4.1.1 Decelerations mapping

First idea that could help to understand the data was to visualize how vehicles accelerated and decelerated. In order to do that a spatial representation of average decelerations was created as it it shown of Figure 13. Track was divided into 4-meters-long segments and for each segment total value of decelerations was summed up over all vehicles and all frames in current phase. Results were plotted for first and second scenario for group 1.

It can be observed from the plot that once multiple autonomous cars were introduced, vehicles decelerated harder and more often when approaching the intersection.

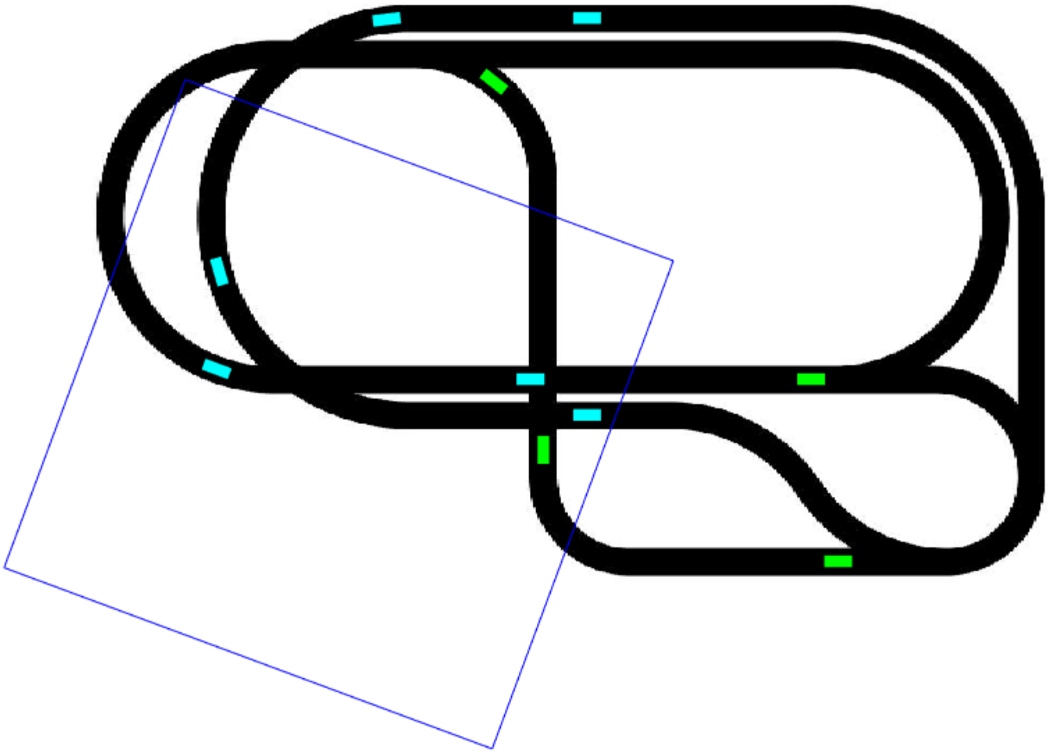
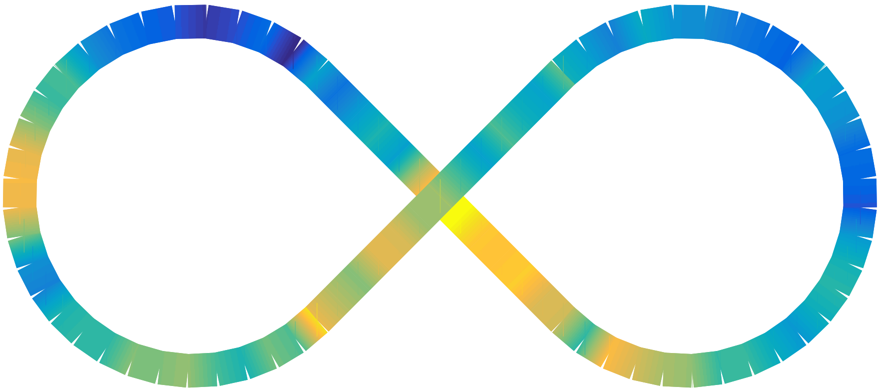


Figure 12: Group 2, phase 3. A snapshot from simulation playback. Cyan colour represents human-driven cars and green represents autonomous cars. A dark blue rectangle represents the view field for one of the cars.

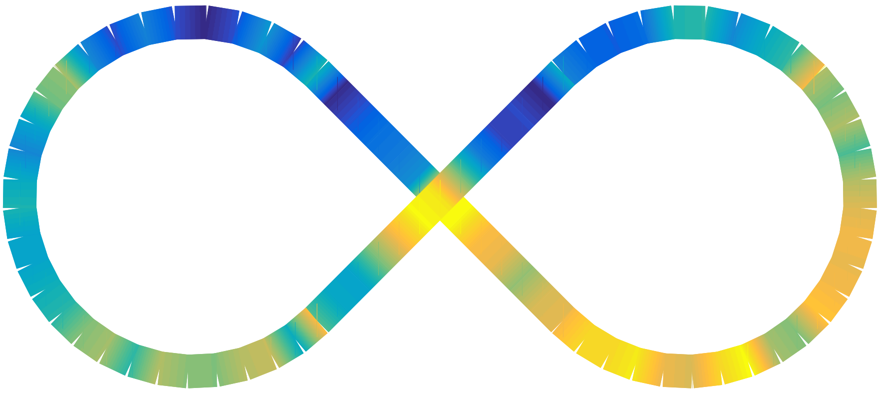
4.1.2 Evaluation of participants' performance

Number of collisions caused by each participant was evaluated and compared against questionnaire responses. Single collision always involved 2 cars. A person responsible was always the one whose car front line intersected the other car first. A number of collisions caused by each person is shown on Figure 14. Table 6 shows number of collisions against questionnaire responses. Becouse the shorters phase lasted 3:22 minutes, values were calculated only for that period for all phases. From these figures it can be seen that:

- Almost every person in the first group performed significantly better in terms of number of collisions than participants from the second group. Because of this reason first group was used more often in further analysis as a sole source of data.



(a) Group 1, Scenario 1



(b) Group 1, Scenario 2

Figure 13: Visual representation of decelerations on map used in first and second scenario. Dark blue represents strong deceleration while light yellow represents weak deceleration. The data was averaged over all vehicles including human-driven and autonomous one.

- Autonomous cars were responsible for only one collision throughout entire experiment.
- In total 52 collisions occurred between two human drivers while 33 happened between human drivers and autonomous vehicles. However, accounting for how much each vehicle spent on the track .... ?

4.1.3 Conflicts resolution

Interactions between cars can be systematized as one car following another or as a broad range of interactions at intersections. The later was of particular interest because of it's uncertainty and unpredictability. While all maps featured intersections, figure of eight map used

Partici-pant	**Familiar with keyboard car control?**	**Years of driving experience**	**Past accidents**	**Driving skill evaluation***	**Driving style****	**Collisions (H/A)**
Group 1						
1	Yes	2	0	2	Very careful	**1/2**
2	Yes	1	1	8	Careful	**4/2**
3	Yes	5	0	8	Normal	**0/2**
4	Yes	6	0	9	Careful	**2/2**
5	Yes	5	2	7	Careful	**3/1**
6	Yes	2	2	10	Normal	**2/0**
Group 2						
1	Yes	No licence	-	-	-	**11/5**
2	Yes	3	1	9	Normal	**7/6**
3	Yes	8	0	8	Careful	**4/5**
4	Yes	15	3	10	Normal	**8/5**
5	Yes	8	2	8	Agressive	**5/1**
6	Yes	3	0	1	Very careful	**4/1**

Table 6: Questionnaire responses represented against number of collisions caused by each person. It can be observed that self-assessment of driving did not correspond to the number of accidents. (*Own judgement of driving skills on the scale from 1 to 10. **Own judgement of driving style from very careful to very aggressive. Please refer to appendix for details.)

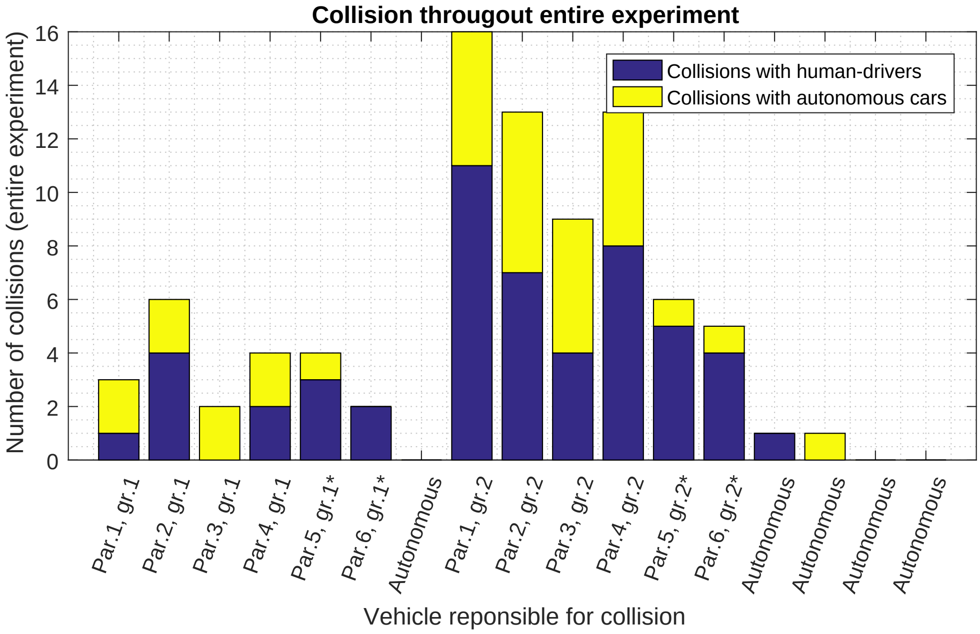


Figure 14: Number of collisions caused by each participant/vehicle in first and second group. (*Humans substituted for autonomous cars in later phases.)

in first two scenarios was aimed at more organized analysis and will be used in this example to visualize how humans and autonomous cars made decisions. Figure 15 shows an example of interaction between one human-driven and two autonomous car. In this example both vehicles at the front came to full stop. In ideal situation one vehicle should pass while the other slows down.

***//something on conficts reosultion: some paper/ nash equlibrum //some paper on interaction between autonomous cars

Another type are interactions between two autonomous cars as it is shown on Figure 16. When two autonomous cars anticipate collision with each other the one which is slower is ordered to reduce its speed according to the time-to-collision value while the faster one passes through uninterrupted. In most cases this relatively simple rule optimizes the interaction reducing braking to minimum.

//figure of autonomous cars

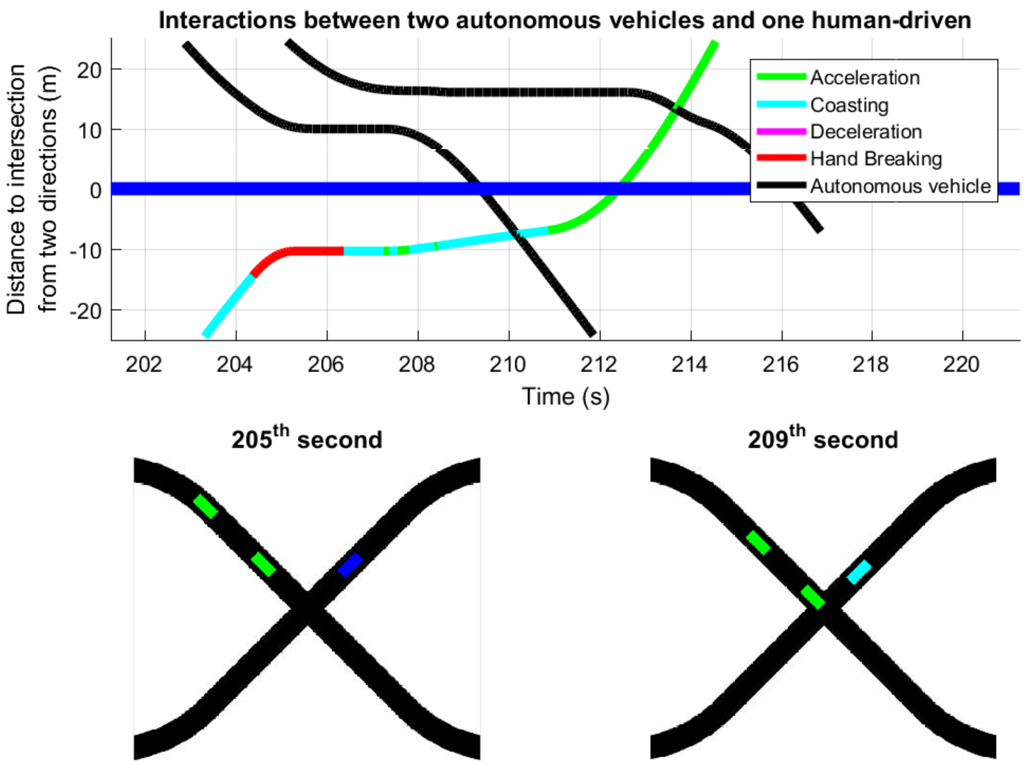


Figure 15: An example of interaction between two autonomous vehicles and one human-driven. In 204th second both cars started to brake to avoid collision and came to full stop. Human driver was uncertain of how the other car will behave. Autonomous car, on the other hand calculated collision free passage as other vehicle was not moving and starter to move through the intersection in 208th second. Next, human passed through and another autonomous vehicle afterwards. (Colours indicate current order from Participant.)

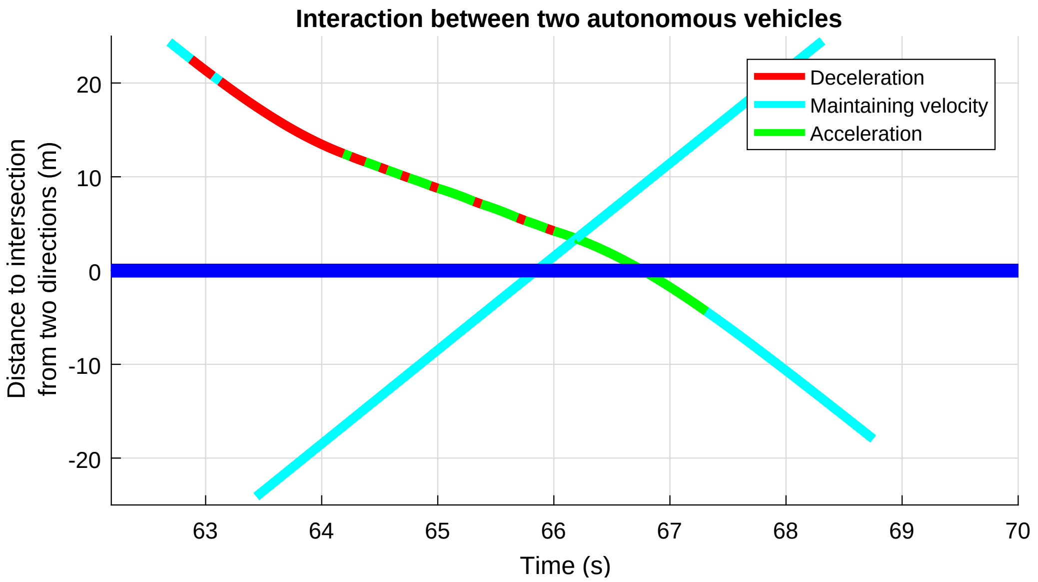


Figure 16: An example of interaction at the intersection between two autonomous vehicles coming from different directions. Both cars anticipated collision in 65th second. In line with the algorithm the slower car started to decelerate as much as it was needed to avoid collision. At each time step new time-to-collision was calculated and velocity adjusted accordingly. The faster car's velocity remained constant.

4.1.4 Reaction times

Another topic of interest were reaction times of both types of vehicles. It was anticipated that the rule to always let human driver pass first and potentially faster reaction by autonomous car would have beneficial impact on the traffic. Particular interest was in differences between reaction times of humans and autonomous cars.

***//use third map here akso...

4.1.5 ***other observations..(TO DO)

DRAFT

also scenario 3

4.2 Hypotheses

4.2.1 Hypothesis: Autonomous cars reduce number of accidents

Based on the observations from previous section it can be seen that autonomous vehicles were almost never responsible for collisions. However, there were numerous collisions caused by other traffic participants involving autonomous cars. Based on these premises the following hypothesis was be tested:

"Replacing part of traditional drivers with autonomous cars reduces number of all kinds of accidents"

Method of analysis The hypothesis was tested by comparing number of collisions in phase 1 and phase 2 in both groups of participants. In order to ensure validity of the results an attempt to identify all factors influencing number of collisions was made. As a result a list presented in Table 7 was created.

According to Vangi & Virga (2007) the deceleration of an average car (Renault Clio®) in good driving conditions, from the speed of $15\ {}^{m}\!/_{s}$ reaches maximum of $12\ {}^{m}\!/_{s^2}$. Although this value might be greater for cars with better brakes it was accepted as a border value. Any situation when deceleration of autonomous car was greater that $12\ {}^{m}\!/_{s^2}$ was analysed separately to classify it as a potential collision.

	Factor	Comment
1	Density of the vehicles.	In phase 1 and phase 2 total number of cars remained constant.
2	Participants improving their skills in vehicle control in consecutive phases.	This factor is hardly accountable for. Its influence was ignored in data analysis however, it was taken into consideration when drawing conclusions.
3	Initial placement of vehicles.	Placement of vehicles was constant through first and second scenario.
4	Length of each phase.	Data was compared over the same length for each phase.
5	The algorithm governing autonomous cars allows for large, unrealistic decelerations.	It was attempted to identify the frequency of these behaviours and its impact on traffic was accounted for.

Table 7: Factors affecting number of collisions.

Findings In first group there were 11 collision in first scenario and 5 collisions in second scenario. In both scenarios there were 3 situation where deceleration of autonomous vehicle reached values below $12\,{}^{m}/_{s^2}$. None of them was classified as potential collision. In second group there were 37 collisions in first scenario and 14 collisions in second scenario. In the first scenario there were 6 situations where deceleration of autonomous car reached values below $12\,{}^{m}/_{s^2}$. None of them was classified as potential collision; In fact these rapid changes of velocity often caused collisions with the car behind which was unable to stop. This should be considered as a flaw in the design of autonomous car algorithm. In the second scenario in second group there were 3 situations where collision was likely prevented by abnormal deceleration of one of autonomous cars. Between first and second scenario number of collision in first group dropped by 55% and by 45% in the second group(including 3 potential collisions). Therefore the following conclusion might be drawn:

Substituting traditional cars with autonomous ones reduces overall number of accidents.

Remarks

- The statement should be verified in further research by accounting for factors mentioned in Table 7.
- Large number of collisions with autonomous cars in third scenario leads to assumption that algorithm governing autonomous cars does not perform satisfactory on more complicated map.
- Differentiating head-on collisions from all other collisions could have impact on the results.

4.2.2 Hypothesis: Autonomous cars smoothed out traffic

All interactions can be segregated into 3 different types: autonomous-autonomous, human-autonomous and human-human. As it was shown before, interactions between two autonomous cars are usually highly optimized. On the other hand, interactions between two humans are random and uncertain by its nature. The third type of interactions involving both human and autonomous vehicle can potentially contain some level of systematicity and

Parameter	Scenario	Group 1 (4 humans)	Group 2 (4 humans)	Group 1 (all vehicles)	Group 2 (all vehicles)
Acceleration variance	1	9.61	12.09	9.14	12.00
	2	7.85	11.39	5.24	8.01
Velocity variance	1	24.70	33.83	24.13	30.56
	2	25.09	29.45	21.37	22.07

Table 8: Average acceleration and velocity variance calculated separately for 4 participants (who took part in both scenarios) and for all vehicles in particular scenario. In can be seen that speed and acceleration variance for humans did not change much between two scenarios. However, when more autonomous cars were introduced the average variance for whole group dropped significantly.

yield better results than solely human drivers. On the basis of these premises the following hypothesis was suggested:

Replacing part of traditional drivers with autonomous cars smooths out traffic (this is not very precise..sth about being start-stopy)

Method of analysis The main measure used to confirm or deny the hypothesis was calculating dispersion of velocities and accelerations for particular vehicles and comparing the results between different scenarios. ...(Dixon & Massey Jr 1957)

First parameter calculated was variance of acceleration. Figure 17 gives variance values for both groups for first and second scenario for particular vehicle. In a similar way variance was calculated for velocities it is shown on Figure 18. Next, mean variances were calculated for 4 people in each group who took part in both phases and independently for all vehicles in each phase. Results are summarized in Table 8.

Findings From one point of view the impact of autonomous cars is clearly visible - average variance dropped significantly. However, if only humans are taken into consideration the differences are considerably slighter. Acceleration variance declined by 18.3% for first group and by 5.7% for second group. Velocity variance in fact rose by 4.1% for first group and declined by 12.9% for second group. Additionally, accounting for the fact that people's driving skill improved each round the hypothesis can be only partly confirmed:

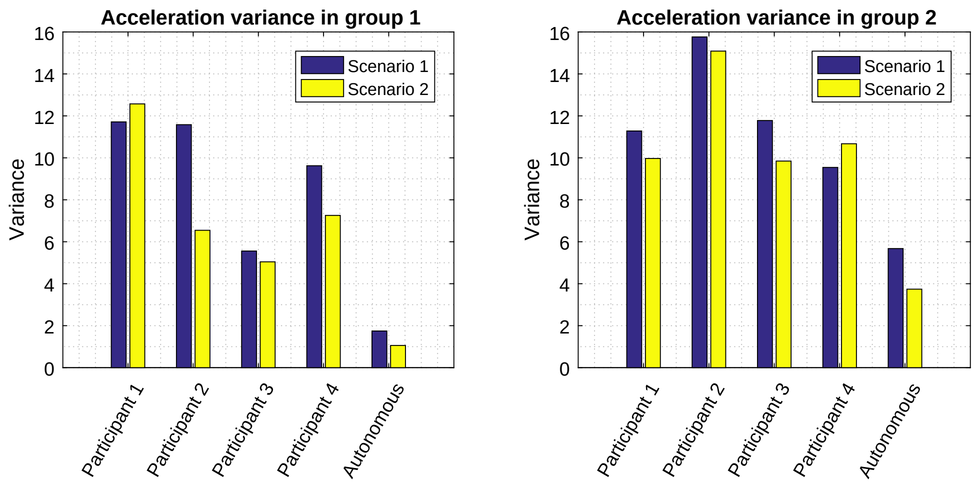


Figure 17: Acceleration variance values calculated for 4 participants that took part in first and second phase and 1 autonomous car. The obvious observation is that autonomous car's acceleration varies very slightly compared to any human driver. Another observation is that variance dropped for 6 out of 8 participants when autonomous cars were introduced.

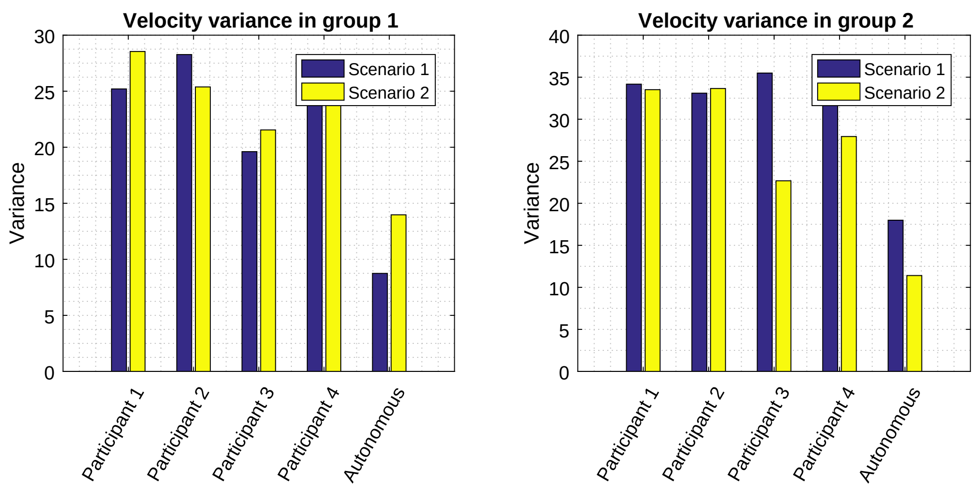


Figure 18: Velocity variance values calculated for 4 participants that took part in first and second phase and 1 autonomous car. Similar to previous figure the variance values for autonomous cars were lower than those of human. However, for human drivers hardly any pattern is observable between first and second scenario.

From the point of view of global traffic performance replacing part of traditional drivers with autonomous cars smooths out traffic since there are fewer human drivers who drive less systematically than autonomous cars. However, from the point of view of particular driver the presence of autonomous cars did not prove to have evident impact on driving smoothness.

4.2.3 Hypothesis: Most efficient traffic could be achieved with solely autonomous vehicle

According to (paper) most benefits of autonomous cars will be experienced only when human drivers will completely disappear from roads. In previous section it was shown that autonomous cars exhibit highly efficient interactions with each other. In line with these examples very good traffic parameters should be observable for simulation involving only autonomous cars. The following hypothesis was proposed:

For traffic consisting solely from autonomous cars parameters such as: total distance covered, acceleration variance and number of collisions should improve in comparison to traffic consisting of both types of vehicles.

Method of analysis In order to evaluate the hypothesis a simulation on map used in first and second scenario with 7 autonomous cars and no human drivers was conducted. Apart from measuring parameters mentioned in the hypothesis it was checked whether any kind of equilibrium is reached for this particular shape of the track. In addition to this, trials with different densities of vehicles were made using map from the third scenario.

Findings A trial run on the map from first and second scenario showed there were no collisions at all. Total distance covered by all cars was 13.4 km. For first group this value was 11.27 km in first scenario and 9.96 km in second scenario. Therefore autonomous cars travelled further even though their velocity was limited to $10\,{}^{m}\!/_{s}$ which was 33% lower than what human-driven cars were capable of. Average variance on acceleration was 0.7850 which was 11 times smaller than the smallest value from scenario 1. Values for particular vehicles are shown on Figure 19. Next, it was investigated whether cars reach velocity equilibrium. The results showed that indeed equilibrium is reached after 1.5 minute (Figure 20). However, the worth of this measure can be little of none. The simulation was run on a closed track with

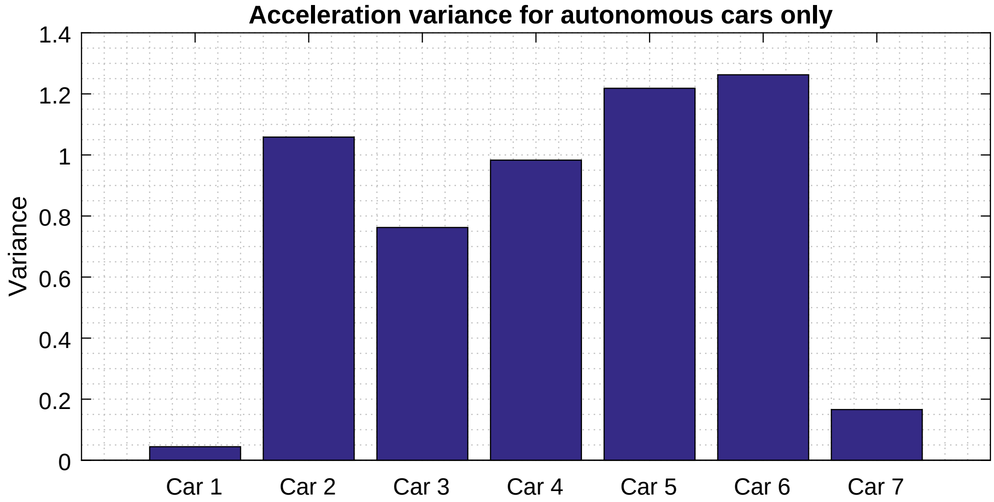


Figure 19: Variances of acceleration for simulation involving only autonomous cars. The values for each car were multiple times lower than in any trial with human drivers. Additionally cars 1 and 7 travelled with even less interruption. This is probably because their initial placement allowed to reach maximum speed before other vehicles. Consequentially they were always given higher priority at the intersection.

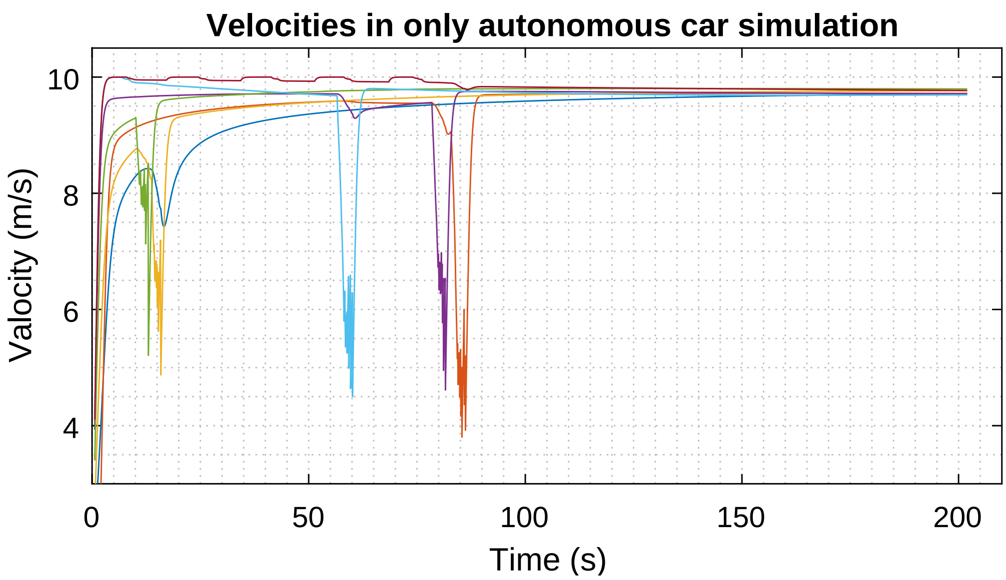


Figure 20:

no intersections and there was no randomization introduced at any point of the simulation apart form the initial placement of vehicles.

***..write more about it...

4.2.4 Hypothesis: Interactions were better between two human drivers rather than human and autonomous

DRAFT ***DRAFT*** ***DRAFT*** ***DRAFT*** ***DRAFT***

statement of the hypothesis Premise: autonomous car algorithm make them always give way to humna driver if the collision is anticipated. However, if the human driver will also slow down it might be possible that autonomous car will not anticipate collision any more and will start to move. This can cause another

Method of analysis what is the method and why it makes sense

- run trials with only autonomous cars. 7 cars on figure of 8 and 8 cars on scenario 3. Additionaly enlarge number of vehicles to maximum for figure of 8 (or scenario 3 too?) -find if velocity reaches some equilibrum..

Findings Describe you you did and what you got as a results

5 Conclusions

TO DO

releta to questionaire reponses..?

relate to all hypotheses and say what the results actually mean.

TO DO

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